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IIASA Working Paper

WP-94-080

September 1994

Working Paper

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Preface

In many areas in Europe present ambient concentration levels of ozone are considered as a serious air quality problem. Current scientific understanding of ozone formation mechanisms suggests that only a balanced cut of the major precursor emissions (nitrogen oxides and volatile organic compounds) will effectively lead to a decline of ozone concentrations over larger areas. Consequently, a systematic framework will be required to explore various strategies to reduce exposure of human beings and sensitive ecosystems to elevated ozone concentrations and to identify cost-effective approaches. Such an integrated assessment has to incorporate information on emission sources, the technical potential and the costs of emission reduction measures as well as an understanding of the chemical processes influencing ozone formation.

This paper, written within IIASA's Young Scientists Summer Programme, provides an initial overview on the available information material and associated costs of the major options for controlling emissions of volatile organic compounds. Thereby, it makes an important contribution to the ongoing development of a tool for the integrated assessment of the tropospheric ozone problem.

Acknowledgements

This paper results from a three months stay at IIASA during the summer of 1993, where the author participated in the Young Scientists Summer Program. The study has been financially supported by the USA member organization of IIASA. The author appreciates the critical comments and suggestions offered by Zbigniew Klimont, Ger Klaassen and Markus Amann.

Birgit Caliandro

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1. Introduction

Ground level, or tropospheric ozone, is an air pollution problem that has received increasing public attention as its impacts become more noticeable and studied. Ozone is formed in the troposphere as a product of a complex set of reactions that involve volatile organic compounds (VOCs) and oxides of nitrogen (NO_x) (NRC, 1991, p. 163). The ratio of NO_x to VOCs, as well as timing and meteorological conditions are among the critical factors determining the concentration of ozone formed. This complex chemistry creates uncertainty in the percentage of VOCs required to reduce ozone formation. The ratio of NO_x or VOC concentration to ozone levels is nonlinear, meaning that a decrease in either of these precursors doesn't necessarily result in a decrease in ozone formation. In fact, a decrease in NO_x or VOC emissions can sometimes lead to an increase in ozone formation.

Increased ground level ozone is a health hazard to people, detrimental to plant and animal life, and leads to the degradation of materials such as plastic and rubber. For these reasons, ozone is an international concern because it, as well as specific VOC species, is transported over long distances and knows no boundaries. To address the problem of VOCs and ozone, European countries signed a VOC Protocol in November 1991. The protocol proposed a 30 percent reduction in anthropogenic VOCs by the year 2000 (Mayeres et al., 1993, p. 108). This action works in conjunction with the Sofia Protocol of 1988 which requires that NO_x emissions cannot exceed 1987 levels by the end of 1994 at the latest (Alcamo et al., 1990).

This report is grounded by the need for policy makers and scientists to explore the costs and effects of each control option on the balance of pollutants when considering scenarios for reducing tropospheric ozone and working toward the goal of maximizing emission reduction. In addition to the numerous sources of VOCs, different control measures reduce VOCs with a range of efficiencies and costs. Policy decisions must therefore be weighted by the contribution of the source, the cost of a specific control measure, its efficiency for removing VOCs and ultimately its impact on ozone concentrations and related other pollutants. These different layers of analysis are necessary in order to evaluate VOC control options and their potential outcomes.

International efforts addressing ozone are related to the experiences shared by many countries in efforts to reduce acid rain. The Regional Acidification INformation and Simulation (RAINS) model was developed at IIASA to evaluate the impacts and costs of strategies to control acid rain (Alcamo et al., 1990, p. 2). The model supports European policy makers in their negotiations of emission reductions under the UN-ECE Convention on Long Range Transboundary Air Pollution. The model already includes NO_x emissions, one component in the formation of both acid rain and tropospheric ozone. Therefore, by adding VOCs to RAINS, the impacts and costs of control strategies for ozone can also be analyzed.

A research project at IIASA is currently working on expanding the RAINS model to include ground level ozone, potentially utilizing the emission inventory from CORINAIR (COoRdination of INformation on the AIR). CORINAIR is part of a comprehensive EC Programme CORINE (COoRdination of INformation on the Environment), providing all kinds of environmental information (land use, air pollution, waste, water pollution, etc.) in Europe (CEC, 1991). The 1990 CORINAIR inventory of atmospheric emissions for Europe is expected to be a primary source of VOC data for the RAINS ozone submodel. Linking the structure of the CORINAIR emission data and the RAINS-ozone model is important.

1.1 Purpose of paper

The purpose of this paper is to give an overview of options, costs and removal efficiencies for VOCs in the context of building ozone into the RAINS model. This paper describes the control options for each sector and reports information on the cost and effectiveness. Due to the great number of VOC species, this paper limits the analysis to VOCs as a single category and does not consider characteristics of specific VOC species. This simplification was necessary for this analysis, however the treatment of VOCs in the RAINS model as one group or in groupings of species, is still under discussion.

The report proceeds in the following order. Section 2 begins with a break out of the contribution of VOCs by source category and explaining the connection between the CORINAIR emission data and the proposed RAINS ozone submodel. In Section 3, control options, removal efficiencies and costs are examined for each emission sector. In Section 4, the cost effectiveness of control options is discussed with ideas for future efforts in this field.

2. Emission sources of VOCs

Volatile organic compounds (VOCs) come from a wide variety of man-made and natural sources. Because of the difficulty in controlling natural sources, efforts to reduce ozone focus on man made emissions. Consistent with other VOC reports, the term VOC is used in this report to include all organic compounds which are capable of producing photochemical oxidants (Rentz et al., 1990, p. 3). As a group, organic compounds include hydrocarbon compounds, and methane. However, methane is excluded here, as in most analyses of tropospheric ozone, because its influence is expected to be minor.

2.1 Emissions by sector

There are a number of transboundary VOC emission inventories in Europe (see Olsthoorn, 1994). The more recent institutional inventories include OECD, CORINAIR (EC), EMEP (UNECE), PHOXA, and LOTOS (TNO). Differences that distinguish these inventories are their spatial resolution, the type of VOCs distinguished, and the source sectors included (Olsthoorn, 1994). These inventories offer information about the emissions sources for VOCs. For this study, emission data from OECD and CORINAIR is used.

As *Figure 1* shows, transportation and solvent use are the two most significant sources of anthropogenic VOCs in OECD Europe (OECD, 1992). The percentage of VOC emissions from each sector will be somewhat different for any individual country. On average, transportation is the largest source within OECD Europe, followed by solvent use, other sources, stationary combustion, gasoline distribution, refineries, other transportation, and the chemical industry (OECD, 1992).

Within the transportation sector itself, gasoline passenger vehicles are the greatest contributor of VOCs (77 percent) followed by motorbikes (10 percent). Reducing VOCs in the transportation sector can be extremely difficult in some places because of the dependence upon the automobile. It is estimated that in Germany evaporative emissions from transportation sources make up almost 20 percent of the sector (CEC, 1991). Heavy duty trucks make up almost nine percent of the transportation sector, whereas diesel passenger cars contribute less than 3 percent. Other transportation sources, such as ships, planes and rail make up approximately 3 percent of the sector.

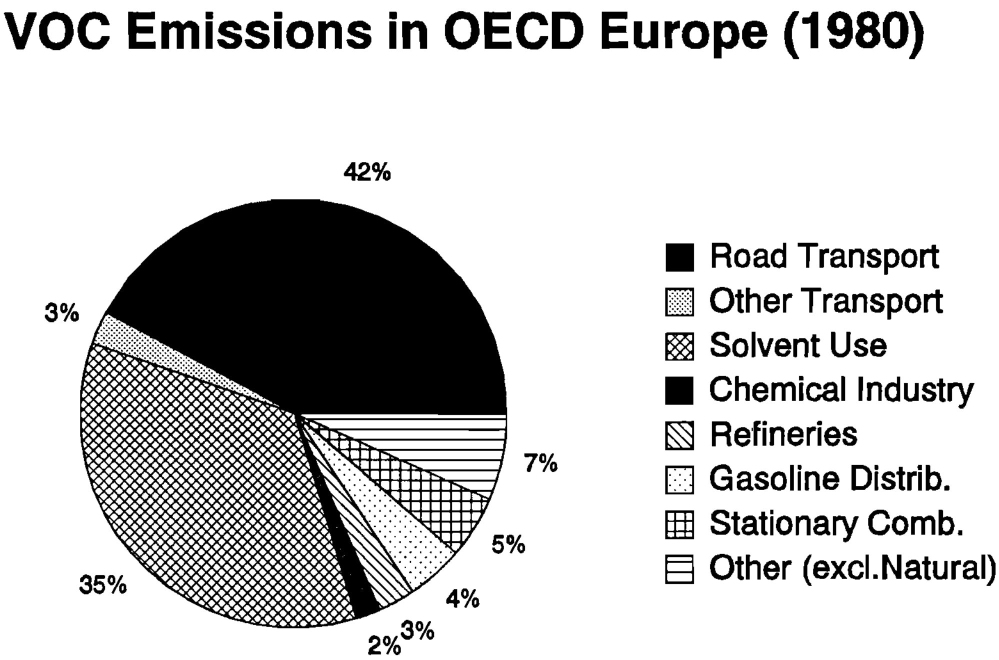

Figure 1. VOC emissions by sector for OECD Europe in 1980

Within solvent use, emissions are split between industrial and non-industrial sources, largely made up of domestic use. Of the industrial sources, metal surface coating contributes most significantly, with about 43 percent of solvent emissions. Degreasing is also an important subsector with approximately 31 percent of the industrial emissions followed by printing and other solvent uses. Domestic sources of VOCs contribute about 55 percent of all non-industrial solvent emissions. Commercial and domestic painting emit about 40 percent, and dry cleaning only 4 percent of non-industrial emissions.

The 'other' sources category, excluding natural sources, is the next largest sector of emissions for VOCs. These sources, such as agriculture, coking, and waste treatment comprise about 7 percent of all VOC emissions.

The remaining sectors, stationary combustion, gasoline distribution, refineries, and the chemical industry each make up 5 percent or less of total emissions. Due to the smaller scale of these sources, specific breakdowns are not evaluated here.

Table 1 shows the amount of kilotons of VOCs emitted by each of the sectors. The table compares the percentage that each sector and subsector contributes. Information from both CORINAIR and OECD is included to illustrate the similarities and differences between these data sources. At the time of writing this paper, the 1985 CORINAIR information is the most current data available on VOC emissions in Europe.

Sector	**Emission [kt]**		**Share [%]**	
	OECD*) 1980	CORINAIR 1985	OECD*) 1980	CORINAIR 1985
Total	11166.2	10029.5	100.0	100.0
Road transport *of which:*	4697.8	4894.6	42.1	48.8
passenger cars - gasoline	3649.2	3790.1	77.7	77.4
motorbikes	457.5	529.8	9.7	10.8
passenger cars - diesel	181.2	113.4	3.9	2.3
heavy duty trucks - diesel	409.9	419.3	8.7	8.6
other road transport**)	-	42.0	-	0.9
Other transport	281.2	-	2.5	-
Solvent use *of which:*	3920.9	3135.2	35.1	31.3
industrial	1945.1	2141.2	49.6	68.3
non-industrial	1975.7	994.0	50.4	31.7
Chemical industry	206.3	338.0	1.8	3.4
Refineries	314.3	188.2	2.8	1.9
Gasoline distribution	487.7	434.3	4.4	4.3
Combustion in stationary sources	529.4	529.9	4.8	5.3
Other	728.7	509.3	6.5	5.1

*) OECD Europe -> EC & EFTA countries; CORINAIR inventory includes only EC countries.
**) LPG engines: passenger cars & LDV

Table 1. Emissions of VOCs in OECD Europe (1980) and EC (1985)

2.2 Link between RAINS ozone sectors and CORINAIR emission data

A framework for applying data from CORINAIR into a RAINS ozone model has been suggested by Olsthoorn (Olsthoorn, 1994). As illustrated below in *Figure 2*, emission data from CORINAIR can be aggregated into sectors for the proposed RAINS ozone model. CORINAIR is organized into eleven sectors, within which there are three levels of increasing detail. This CORINAIR data structure is based upon the system of selected nomenclature for air pollution, known as "SNAP".

In order to simplify the CORINAIR structure for use in an integrated assessment model, Olsthoorn recommends a structure of emission sectors different from CORINAIR (Olsthoorn, 1994), a structure that is also used as the framework for this paper. This proposed framework includes seven source categories: transport, solvent use (industrial and non-industrial), the chemical industry, refineries, gasoline distribution, stationary combustion, and other. Olsthoorn also recommends a category for nature which is not included in this analysis due to the difficulty involved in controlling natural sources as well as the limited information on control costs for this VOC sector.

The proposed framework connects emission data, sources, and control measures so that potential emission reductions can be applied to estimate future changes in emissions.

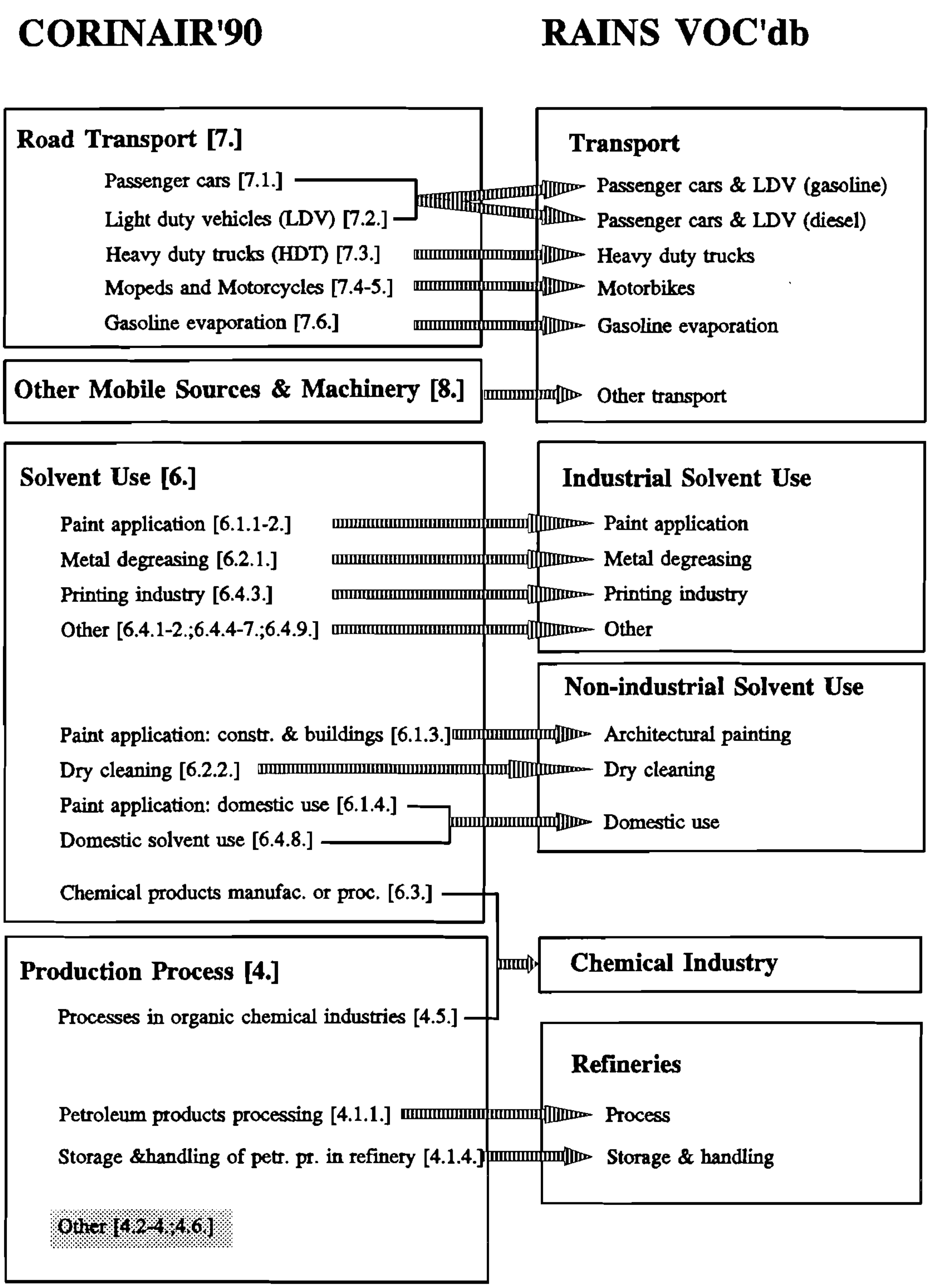

Figure 2. VOC sectors for CORINAIR 1990 and proposed RAINS ozone model

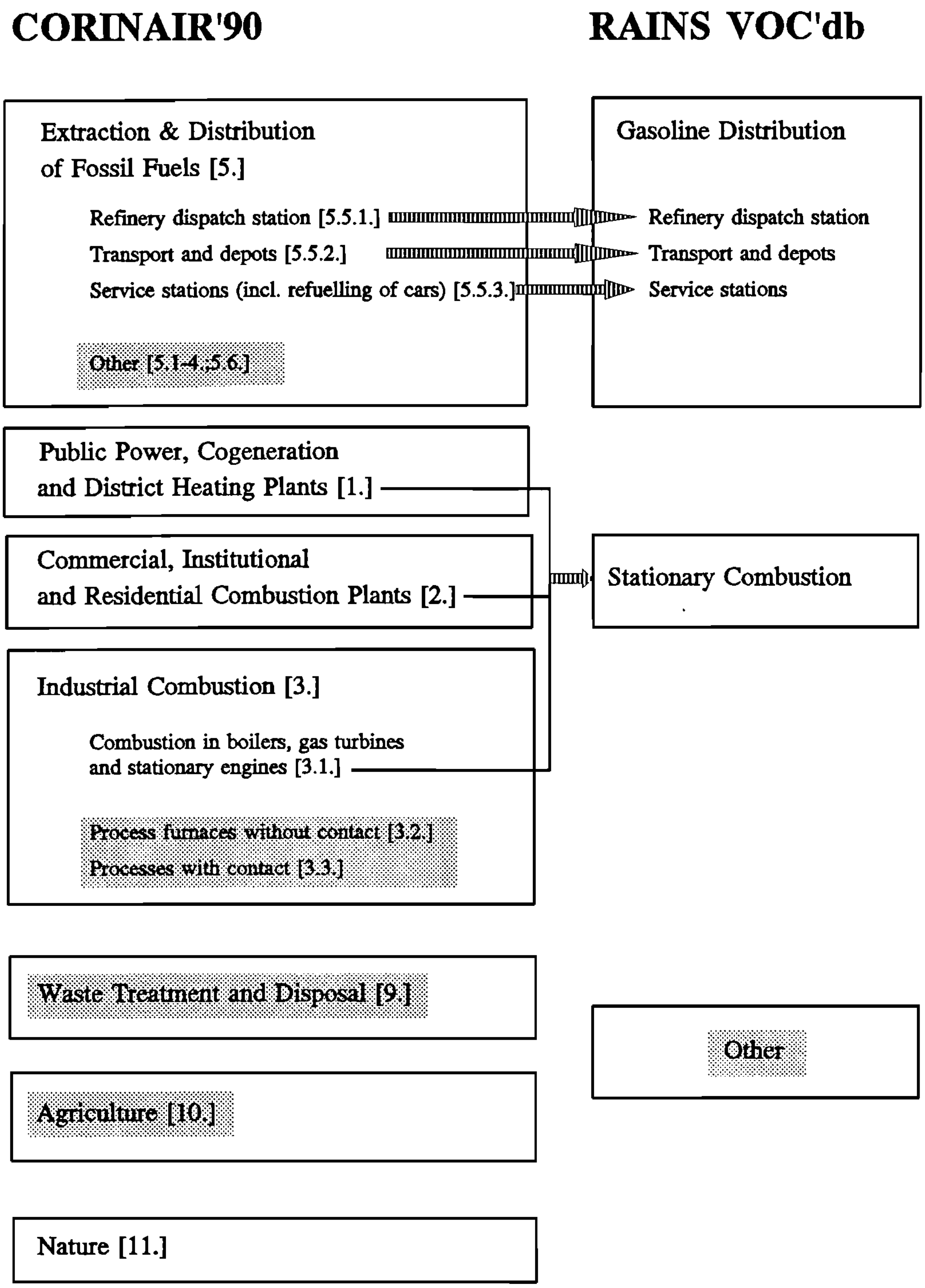

Figure 2 (cont.). VOC sectors for CORINAIR 1990 and proposed RAINS ozone model

3. Review of control technologies and costs by sector

There are different types of control measures for reducing or eliminating sources of VOCs. Control measures that involve altering an existing process or changing a product are considered when cost estimates are available. Another category for reducing VOC emissions is enhancing existing equipment and control technologies to improve their efficiency. Improving the management of currently installed methods with inspection and maintenance is also an option included in this report. Applying technologies like condensation or carbon adsorption enables recovery of solvents. Lastly, substitutes can be used in place of VOCs and also thereby prevent VOC emissions.

Control options can be evaluated in different ways. Two strategies are most common: best available control technology, and least cost. These strategies will not be considered in this paper but such scenarios will be incorporated into the RAINS ozone model. All control options must first be considered individually to assess the relative significance of the source and evaluate whether it significantly reduces the ozone concentration. For this reason, the total emission of a source, as well as the removal efficiency of a control measure, must be taken into account when evaluating options.

Information on control technologies used in this report has been taken from a collection of recent reports, and a variety of sources. Control options are compared with consideration to removal efficiency, the percentage of VOC (and NO_x in some cases) that is removed with a given control option. Costs are compared in terms of the average annual costs, in 1987 European Currency Units (ECU) per ton of VOC removed. In order to compare results, where necessary, costs have been recalculated into ECUs using 1987 exchange rates.

3.1 Road transport

The RAINS ozone submodel will build upon the existing RAINS emissions data for NO_x from vehicles (Amann, 1989). Included in the transport sector are gasoline passenger cars and light duty vehicles, diesel cars and light duty vehicles, heavy duty trucks, motorbikes (and mopeds), gasoline evaporation, and other transport. In some cases, controls have already been required for passenger cars and evaporative emissions.

A number of different options are reported to reduce VOCs from gasoline vehicles (*Table 2*).

In June 1985, most of the EEC member states agreed to a series of emission limits for automobiles and light duty gasoline vehicles, known as the Luxembourg Agreement (Johnson, Corcelle, 1989). The limits are established by engine size and reduce both VOCs and NO_x by approximately fifty percent. Controls under the Luxembourg Agreement include exhaust gas recirculation (EGR), lean burn engines and uncontrolled catalytic converters. Lean burn engines typically need oxidation catalysts to reduce hydrocarbon emissions to specified limits. Lean burn engines also have the advantage of improving the fuel economy of cars, unlike 3-way catalysts which can reduce fuel efficiency (Allemand et al., 1990).

Table 2. Transportation control options, removal efficiencies and costs for gasoline automobiles and light duty vehicles

VOC Control Option	**Removal Efficiency (%)**	**ECU/ton (1987 ECU)**
Gasoline Vehicles		
U.S. 1986 Std (3-way cat.)	90	1000-2500 (a)
3-way catalytic conv. w/I&M	75	920-2433 (b)
3-way catalyst & elec. controls	80	2265 (c)
3-way catalytic conv.	80	920 (d)
Oxidation catalyst	90	1959 (c)
Oxidation catalyst - LDV	55	1896 (e)
Oxidation catalyst w/I & M	55	4032 (b)
Engine modifications w/EGR	35	1582 (d)

(a) Amann, 1989, p. 43
(b) OECD, 1992, p. 43
(c) VHB, 1989, p. 30
(d) ECE, 1990, p. 346
(e) OECD, 1992, p. 44

Inspection and maintenance programs (I & M) are another option, and vary in cost and effectiveness depending upon how they are organized. I & M programs are beneficial in reducing tampering with emission control systems and encourage maintenance of emission control equipment. However, reductions can only be realized if inspections are carried out correctly.

In the United States, I & M programs are just one of the several mandatory programs designed to reduce emissions as a result of the 1990 Clean Air Act Amendments. Additional measures to comply with air quality standards include:

- the design and manufacture of vehicles with lower tailpipe and evaporative emissions,
- use of less polluting gasoline and alternative fuels,

- transportation control measures to reduce the number of vehicle miles travelled.

The cost of these requirements vary depending upon the specific mix. One estimate of the emission control cost for a low emission vehicle program was calculated at $180 per ton removed (NESCAUM, 1991).

Gasoline vehicles and LDVs. The U.S. standard requires a 3-way catalyst which effectively reduces the VOC concentrations in exhaust gases using catalytic converters. Three-way catalytic converters reduce CO, NO_x and VOCs through oxidation to carbon dioxide, H_2O, and nitrogen, whereas oxidation catalysts reduce CO and VOCs. Another control option for gasoline passenger vehicles is engine modification in order to burn hydrocarbons in the exhaust, a common product of incomplete combustion. Engine modifications include using sensors to control the fuel and ignition systems (CONCAWE, 1990, p. 156). In some places, such as the United States, the improvements brought by control technologies are only offset by the increasing number of cars and vehicle miles traveled (NRC, 1992).

The cost for 3-way catalytic converters ranges from 920 to 2500 ECU per ton, (see *Table 2*) with 75 - 90 percent removal efficiency. Oxidation catalysts are reported to range in removal efficiency from 55 - 90 percent, with costs starting at 1959 ECU and ranging up to almost 9000 ECU per ton. Three-way catalysts are reported to be more effective in removing VOCs, using an average of the reported efficiencies. Engine modifications are the least effective although comparable in cost to some catalysts. Engine modification and EGR are typically used to reduce NO_x and are less effective in reducing VOCs.

Diesel vehicles. Diesel vehicles are not as large a source of VOC emissions as gasoline vehicles; 3 percent compared to 77 percent of the transportation sector emissions, respectively, but are increasing their share. There is also less information about diesel vehicles and trucks compared to gasoline. Diesel vehicles emit fewer VOCs, and improvement options center around engine modifications or fuel quality. In the existing RAINS model, two options for diesel vehicles are considered, however only one reduces VOCs in addition to NO_x (see *Table 3*). The U.S. 1991 standard involves changes in engine design and combustion systems (Amann, 1989, p. 25). The other option for reducing VOC emissions from diesel vehicles requires changing the quality of the fuel. This option does not remove VOCs as effectively as the latest technology for diesel engines.

Table 3. Transportation control options, removal efficiencies and costs for diesel vehicles, heavy duty trucks and motorcycles

Control Option	**Removal Efficiency %**	**ECU/ton (1987 ECU)**
Diesel Vehicles		
U.S. 1991 Stds.	50	1400-6700 (a)
Autos - Improved Fuel Quality (IFQ)	15-20	300 (b)
Light duty vehicles - IFQ	20	324 (c)
Heavy Duty Trucks		
Cetane improvement by additive	15	109 (d)
Cetane improvement by process	15	1269 (d)
Motorcycles		
Engine modification & EGR	35	4297 (e)
Oxidation catalyst	55	4731 (e)
Oxidation catalyst w/ I&M	75	7562 (e)

(a) Amann, 1989, p. 43
(b) ECE, 1990, p. 36
(c) OECD, 1992, p. 46
(d) OECD, 1992, p. 48
(e) OECD, 1992, p. 45

Options to reduce VOCs for diesel vehicles are neither costly nor very effective. Improving diesel fuel quality is one of the less expensive alternatives, however the reported removal efficiency is small.

Heavy duty trucks. Information for control options for heavy duty trucks was found only for changes in diesel fuel quality (see *Table 3*). Other options, however, exist, such as improved timing but cost estimates were not found. The cetane number of a diesel fuel is an indication of its ability to ignite in the engine. VOC emissions increase with a decreasing cetane number (Allemand et al., 1990, p. 167).

Motorcycles. Control options for motorcycles, similar to gasoline vehicles, include engine changes and exhaust gas recirculation (primarily to reduce NO_x) or oxidation catalysts. Oxidation catalysts are more expensive, but considerably more effective for reducing VOCs, ranging between a 55 - 75 percent removal efficiency. Oxidation catalyst reduce VOCs and CO primarily. A range of removal efficiencies have been reported, with an average of approximately 65 percent (*Table 3*).

On-board emission control. Controlling evaporative emissions from motor vehicles is important, however the cost effectiveness varies among control methods. On-board emission controls are designed to capture VOC released during refueling and evaporative emissions (running and hot soak losses). On-board emission controls typically refer to carbon canisters which collect vapors from the car's fuel system. Smaller canisters can absorb VOCs from hot soaks and diurnal losses, whereas larger canisters also absorb VOCs released during car refueling (Olsthoorn, 1994).

Reported costs for on-board controls vary (see *Table 4*) but effectiveness is consistently estimated at about 90%. The cost of on-board canisters to collect VOC emissions from fuel tanks and engines range between 200 and 1165 ECU per ton VOC removed. The removal efficiency is reportedly 90 to 95% effective. This control option can be phased into car production over a short period of time.

Table 4. Transportation control options, removal efficiencies and costs for on-board emission controls and other transportation

Control Option	**Removal Efficiency %**	**ECU/ton (1987 ECU)**
On-Board Emission Control		
Large canisters	90	200 (a)
Evaporative losses (1 liter)	90	290 (b)
Vapor recovery (8 liter)	95	780 (c)
Refueling losses	90	1165 (b)
Other Transport		
Rail - Vapor Recovery Unit	89	1529 (d)
Ship - Vapor Recovery Unit	90	2823 (d)
Barge - Vapor Recover Unit	89	3860 (d)

(a) ECE, 1990, p. 346
(b) CONCAWE, 1987, p. 12
(c) OECD, 1992, p. 69
(d) ECE, 1990, p. 331

Rail, ships, and barges. Other transportation sources include rail, ships and barges. Fugitive emissions and spillage are the greatest source of VOCs from these sources. Control options consist of vapor recovery or collection systems that prevent emissions from escaping during transfer and reduce fugitive emissions during storage. Emissions from this category can be effectively reduced with vapor collection systems. These units range in cost between 1530 and 3900 ECU per ton of VOC removed (*Table 4*). This subsector is not a significant contributor, and therefore these costs may not be warranted depending upon the specific country.

Alternative fuels. A number of alternative fuels are attractive options because they can reduce and even eliminate some VOCs and other air pollutants. In the short term, reformulated gasoline is the only alternative fuel that can reduce ozone concentrations (NRC, 1991, p. 381). Some of these reformulated fuels are already on sale in the more polluted cities in the U.S. However, the effectiveness of this reduction strategy is uncertain. In the next 5 to 20 years methanol, natural gas, liquified petroleum gas (LPG) and hydrogen are expected to become more viable fuel alternatives with further research and investments made toward new distribution systems. Electric vehicles are also expected to develop as an option, and offer the greatest improvement in air quality by eliminating vehicle emissions (NRC, 1991, p. 430). Cost estimates for these alternative fuels were not found.

Cost comparison. Within the transportation sector, evaporative emission controls and catalytic converters cost less than some other alternatives and have the benefit of high removal efficiencies. Three-way catalysts appear to be the most effective in removing VOCs from gasoline vehicle exhaust (CONCAWE, 1987). CONCAWE reports that the combination of reduced gasoline vapor pressure and Stage II controls (systems to reduce fugitive emissions while dispensing automobile fuel at service stations) is less cost-effective than on-board canisters (CONCAWE, 1987, p. 10).

3.2 Solvent use

Industrial. Industrial solvent use includes paint application, known as surface coating (SC), metal degreasing, printing, and other uses. There are several options for reducing VOCs in the painting industry depending upon the type of painting, or surface coating, and processes. One well documented subsector in the painting sector is automotive painting (see MacDonald, 1991). This makes up approximately 40% of all industrial painting. Control options, as outlined in *Table 5*, include thermal and catalytic incineration where VOCs are burned, carbon adsorption and low solvent coatings.

Painting. The least expensive control option for paint application is the use of low solvent coatings followed by carbon adsorption. One case reports a 99 percent removal efficiency for carbon adsorption. Water-based inks and carbon treatment are more cost-effective and have removal efficiencies similar to the incineration options. Commercial water-based coat is not one of the more expensive alternatives and in principle has an efficiency close to 100%. This option could be applied to reduce emissions in private and commercial surface coating. In a study prepared for Environment Canada (VHB, 1989), removal efficiency of 25 percent is given for this option which is due to the assumption that only 25% of emissions from this sector could be controlled. As noted in *Table 5*, high solids are reported to be the most expensive option for printing, followed by incineration.

Table 5: VOC control options, removal efficiencies and costs for industrial painting

Control Option	Removal Efficiency	ECU/ton (1987 ECU)
Paint application		
Automotive - low solvent	70	189 (a)
Automotive - SC, process change	70	797 (b)
Automotive - SC, high solids	88	8958(b)
Automotive - SC, incineration	80	2817(b)
Automotive - carbon adsorption	99	310 (c)
Metal SC - low lolvent	-	189 (d)
Metal SC - incineration or CAD	-	396 (d)
Water based coatings - commercial	25	895 (b)

(a) OECD, 1992, p. 18
(b) VHB, 1989, p. 25
(c) OECD, 1992, p. 70
(d) Allemand, 1992, p. 123

Printing. In the printing sector, lithography is the most common technique, followed by rotograve (Rentz et al., 1990). There are at least five options to reduce VOCs from the printing subsector. First, water-based inks or low solvent inks can be substituted for solvents. Another option is activated carbon adsorption, however recovered solvents are not reusable because of the number of different species collected (Rentz, 1990, p. 161). Thermal or catalytic incineration reported a high efficiency and has the option of a heat recovery unit. Absorption is a final option which is being tried in some places (Rentz, 1990, p. 163).

Control options for printing range in cost from 420 to 7880 ECUs per ton VOC removed (*Table 6*). As with painting, the less expensive alternatives use water-based inks. Carbon treatment and process changes cost approximately 700 to 800 ECU per ton removed. Installation of incineration processes is again the most expensive alternative due to the investment cost. However, incineration with heat recovery is not reported to be any more effective than water-based paints.

Table 6: VOC control options, removal efficiencies and costs for industrial printing

Control Option	Removal Efficiency %	ECU/ton (1987 ECU)
Printing		
Water-based ink - roto & flexography	70	419 (a)
Carbon treatment	85	713 (b)
Process change	70	797 (b)
Incineration	90	4225 (b)
Catalytic incin. w/heat recovery	69	5389 (c)
Thermal incin. w/heat recovery	69	7881 (c)

(a) OECD, 1992, p. 76
(b) VHB, 1989, p. 25
(c) OECD, 1992, p. 77

Metal degreasing. In degreasing, solvents are used with alkaline cleaners to degrease metal surfaces before soldering, painting, or surface treatment (CONCAWE, 1987, p. 143). Typically, machines have open tops for manual use, or are enclosed for mechanical handling (CONCAWE, 1987, p. 147). Machine design and improper use commonly lead to evaporative emissions. To reduce emissions, covers can be automated, freeboards can be heightened and refrigerated, and water-based systems can be substituted for the solvents.

Compared to printing, there are fewer control options reported for metal degreasing. Carbon treatment is reported to cost 15 ECU per ton removed with an efficiency of 70 percent. Installation of covers on the degreasing machines, chilled freeboards, and carbon adsorption is reported to result in a zero cost per ton removed (OECD, 1992, p. 75).

Other industrial solvent uses. Other solvent control measures can be applied to the solvent use in general. Similar to other industrial solvent uses, general options include carbon adsorption, and catalytic and thermal incineration. These more general processes appear to be comparable in their effectiveness but vary in cost from 193 to 768 ECU per ton (see *Table 7*), thermal incineration being most expensive.

Cost comparison. In general, the more cost-efficient control options for industrial solvent use include:

- carbon adsorption for painting as well as for general use,
- installing machine cover and chilled freeboards for metal degreasing,

- process changes, such as water-based ink, are least costly in the printing sector, as well as carbon treatment.

Table 7: VOC control options, removal efficiencies and costs for metal degreasing and other

Control Option	Removal Efficiency %	ECU/ton (1987 ECU)
Metal Degreasing		
Metal cleaning w/carbon treatment	70	15 (a)
Machine covers, chilled freeboard and carbon adsorption	60	0 (b)
Other		
Carbon adsorption	90	193 (c)
Catalytic incineration	90	502 (c)
Thermal incineration	90	768 (c)

(a) VHB, 1989, p. 25
(b) OECD, 1992, p. 75
(c) OECD, 1992, p. 71

Non-industrial solvent use. Non-industrial solvent use includes architectural painting, dry cleaning and domestic uses of solvents. Reducing VOCs from architectural painting can lead to changing to low-solvent or water-based paints in building and construction (see *Table 8*). High solids paints can contain up to 30 percent solvents and are more expensive than other traditional paints (Allemand et al., 1990, p. 29). Reducing solvents in paints and powder coatings are control options with low or negligible costs.

To reduce VOCs from dry cleaning, exhaust treatment systems must be installed. Typically, VOCs are emitted from cleaners as a result of poor maintenance or operating procedures. Technical controls to reduce emissions are used in enclosed dry cleaning machines and adsorption cartridge filters.

The emission from domestic (household) use of solvents could be reduced either by a process change to reduce the amount of solvent content or substitute the solvent ingredient and change the product.

Among these non-industrial control options, water-based paints are most commonly considered as an option to reduce VOCs. Some countries, such as Denmark, already have geared their paint sector away from the use of solvent and primarily offer water-based products (Allemand, 1992).

Cost comparison. Control options for non-industrial solvent use are similar to industrial solvent uses, however costs are generally less expensive. Reducing solvents and increasing water-based paints range in cost between 0 and 896 ECU. Efficiency also is reported to range from 25-100 percent (see *Table 8*). Based upon the reports examined, closed systems are the most cost-effective controls for dry cleaning (VHB, 1989). Given the equal share of the solvent sector, domestic control technologies are generally more cost-effective than industrial options, which carry higher investments.

Table 8: VOC control options, removal efficiencies and costs for non-industrial solvent use

Control Option	**Removal Efficiency %**	**ECU/ton (1987 ECU)**
Architectural Painting		
Water-based - commercial	25	896 (a)
Water-based - commercial	82	514 (b)
Low solvent - ind. & domestic	45-100	514 (c)
Water-based for wood	65	0 (d)
High solids	45	0 (b)
Powder coatings	100	514 (b)
Dry Cleaning		
Closed system	99	789 (a)
Dry cleaning	50	1491 (e)
Carbon treatment	95	4390 (a)
Domestic		
Process change	90	1791 (a)

(a) VHB, 1989, p. 25
(b) OECD, 1992, p. 70
(c) OECD, 1992, p. 18
(d) OECD, 1992, p. 78
(e) OECD, 1992, p. 19

3.3 Chemical industry

The chemical industry sector includes the solvent use in production, manufacturing and processing of chemicals and processes in the organic chemical industry. Some options are available for the sector in general, while others pertain to the specific type of chemical production (*Table 9*). Retrofitting existing chemical tanks with floating roof tanks or constructing new tanks with roofs prevents the escape of fugitive emissions from the tank as well as during transfer. Incinerating vapors is another control option. These methods do not allow for collection and reuse of VOCs. Catalytic incineration also burns vapors from the source.

Cost comparison. At this time, reports contain limited information on the costs of controlling VOCs in the chemical industry. Flaring or burning exhaust fumes is one of the least costly alternatives. Costs for simple controls are not expensive, however specific controls for chemical production were found to be more expensive, such as for formaldehyde (Rentz, 1990, p. 368).

Table 9: VOC control options, removal efficiencies and costs for the chemical industry

Control Option	**Removal Efficiency %**	**ECU/ton VOC (1987 ECU)**
Internal floating roofs	70-90	- (a)
Incineration	90+	- (a)
Flaring	98	12 (b)
Catalytic incineration	80	230 (c)
Formaldehyde incineration	98	1133 (d)

(a) Allemand et al., 1990, p. 144
(b) ECE, 1990, p. 363
(c) ECE, 1990, p. 365
(d) ECE, 1990, p. 368

3.4 Refineries

The refinery sector includes the processing and storage of petroleum products. In this sector, common methods to control emissions are improving storage facilities, securing valves and leaks, and regular inspection and maintenance of equipment (see *Table 10*). Refineries are not one of the larger emission sectors, but can be a significant source depending on the size of the refineries in a specific country and fuel sources.

Fugitive VOC emissions from refineries can be controlled by improved seals and inspection and maintenance. Recovering vapors and VOCs from tanks is also an option. Control systems collect and usually burn vapors to prevent them from being released to the environment. Floating covers on storage tanks (known as Stage IA controls) also help to prevent VOCs from accumulating in the tank and then being vented to the outside.

Another option is reducing the volatility of gasoline, indicated by the Reid Vapor Pressure (RVP), to prevent evaporative emissions throughout the product life of gasoline. Reducing gas volatility at the refineries also reduces evaporative emissions during gasoline distribution. This option is currently being used during the summer months in parts of the United States. The 13 percent removal efficiency includes the entire fuel marketing sector, including vehicle refueling. The cost of reducing the volatility is only associated with the refinery sector. The benefits are passed on from refineries, to distribution, and transportation. CONCAWE reports that reducing the volatility has a significant, but less of a reduction of VOCs than other types of vapor control systems (see *Table 10*).

Cost comparison. Data collected on refineries has a range in costs from zero to over 10,000 ECU per ton VOC removed (*Table 10*). This can be accounted for by the range of simple measures, such as inspection and maintenance programs, to more capital intensive options such as floating decks on tanks. Reducing gas volatility is the least effective and one of the more expensive options. Installing floating covers and secondary seals are a better investment in terms of reducing emissions at a lower cost.

Table 10: VOC control options, removal efficiencies and costs for refineries

Control Option	**Removal Efficiency %**	**ECU/ton VOC (1987 ECU)**
Fugitive emissions-quarterly	80	193 (a)
Inspection & maintenance	-	106 (b)
Secondary seals	89	163 (c)
Floating covers	90	165-643 (d)
Internal floating deck	54	2088 (e)
Reduced gas volatility	13	2006 (f)
Retrofit fixed roof w/covers	89	10435 (g)

(a) OECD, 1992, p. 18
(b) Mayers, 1993, p. 123
(c) OECD, 1992, p. 61
(d) OECD, 1992, p. 60 and Mayers, 1993, p. 123, respectively
(e) OECD, 1992, p. 62
(f) VHB, 1989, p. 25
(g) ECE, 1990, p. 293

3.5 Gasoline distribution

The gasoline distribution sector includes distributing gasoline from refineries and transferring and depositing it at service stations. During distribution, VOCs are emitted as vapors are released and fuel is spilled. As a result, control options for gasoline distribution focus on preventing evaporative losses by improving gasoline lines and seals and installing vapor collection systems, also known as Stage IB and II controls.

Stage II controls are common for controlling VOC emissions during distribution of gasoline at service stations. Estimates of the effectiveness of this vary and depend upon whether the equipment is properly installed, used and maintained. The variance in cost can be accounted for by the different sizes of service stations and businesses, as well as local prices for labor and materials for installation.

Vapor Recovery Units (VRU) remove VOCs from the tanks or loading operations typically by condensation, liquid adsorption or a combination of these processes. The collected VOCs are returned to the tank in liquid form. Estimates for cost and efficiency can vary depending upon the size of the service station.

Another important component of controlling VOC emissions during gasoline distribution is the seals and lines of the trucks. There are bottom and top loading vehicles, each of which require well maintained equipment to prevent spills during transfer. Bottom loading vehicles are considered by some to be more effective than top loading for maximum vapor recovery (CONCAWE, 1990, p. 57).

Cost comparison. Secondary seals are reported to have a negative to zero cost making them the most attractive control option (see *Table 11*). In addition, vapor recovery and balancing can both be cost-effective options. Larger terminals can achieve greater cost-efficiencies (CONCAWE, 1990, p. 57) and thereby potentially reduce estimated costs of controls.

Table 11: VOC control options, removal efficiencies, and costs for gasoline distribution

Control Option	Removal Efficiency %	ECU/ton VOC (1987 ECU)
Refinery Dispatch		
Vapor recovery at loading	89	1580 (a)
Transfer & Depot		
Vapor balancing at transfer	98	286 (b)
Secondary seals on tanks	97	-338 - 0 (c)
Service Stations		
Vapor balance	56	5820 (d)
Vapor balance	95	16 (e)
Vapor recovery	98	172 (e)

(a) OECD, 1992, p. 19
(b) OECD, 1992, p. 66
(c) OECD, 1992, p. 65
(d) CONCAWE, 1990, p. 56
(e) VHB, 1989, p. 25

3.6 Stationary combustion

Stationary combustion includes public power, cogeneration, district heating, commercial, institutional, and residential heating, industrial boilers, and refinery processes furnaces. No information about methods and costs for reducing VOCs in the stationary combustion sector was available. There are changes that would result in a reduction in VOCs. Such options include using alternative fuels, for example from coal to natural gas, conserving energy and therefore reducing the demand for generating electricity, and improving maintenance programs at power generation facilities.

3.7 Other

No information about methods and costs for sources in the other category, such as agriculture and waste treatment, were found.

4. Conclusions and recommendations

Over one hundred control options for reducing VOCs were reviewed for this paper. Many of these control options are in the process of being developed and tested while others are implemented. This paper provides a preliminary list of the most cost-effective control strategies based upon reported estimates. However, the cost figures given are influenced by many factors and are very case-specific. The estimates represent order of magnitudes rather than absolute cost estimates. This is especially important when discussing cost-efficient emission reduction strategies.

4.1 Explanation for cost differences

This paper arrives at two major conclusions:

- Costs of applying the same technical option to reduce VOC emissions in some cases may vary widely, and it is not always clear why such large cost differences occur (for example the cost of vapor balancing from 16-5820 ECUs, as indicated in *Table 11*).

- Given the uncertainty in cost estimates it appears that some options are clearly more cost-effective means for controlling VOC emissions than others.

Cost and efficiency estimates have been collected from various sources, mainly studies performed by OECD (OECD, 1992), CONCAWE (CONCAWE, 1987, 1990), UNECE (Rentz et al., 1990), CEC (Allemand et al., 1990, 1992). Given the limited background information in some reports, it is difficult to calculate exactly why some costs (and efficiencies) vary. Some possible reasons are suggested below.

Defining costs. The cost-effectiveness of a control option is defined as ratio of annual costs per ton emission reduction. The methodology used to calculate costs in reviewed studies is in principle the same but several assumptions are different. Some of the differences are:

- Different assumptions on major parameters such as discount rates, plant lifetime, financial outlays versus real resource costs. For example CONCAWE assumes 25% charge on investment (annual capital charge) (CONCAWE, 1987) while CEC uses 10% (Allemand et al., 1990).
- Some of the cost calculations attribute half of the cost of the control technology to NO_x and

VOCs each. This cost separation is not performed for all estimates and not addressed in some reports. Whether costs have been calculated for just VOCs, or VOCs and NO_x, or all species of air pollution, is not always evident. Separating these control costs for multiple kinds of compounds is especially relevant for the transport sector[1].

- The revenues from recovered hydrocarbons are not taken into account in CONCAWE estimates. In CEC studies the value of 0.2 ECU/kg of recovered VOC is assumed while OECD estimates savings in some categories of control equipment.

Technical efficiencies: expected versus actual efficiencies. Removal efficiencies are less than expected because people do not properly maintain or operate equipment. One study in the U.S. by South Coast Air Quality Management District (SCAQMD) reported that one year (1988) more than 70 percent of 180 facilities audited had underestimated emissions by an average of 15 percent due to poor operations (NRC, 1990, p.87). This was taken into account (to the possible extent) in the study of OECD (OECD, 1992) where quoted reduction efficiencies rely as far as possible on data from real applications of control equipment in OECD countries.

The abatement efficiency of control equipment decreases with time especially when it is not run and maintained properly. Therefore in some cases in the OECD study (OECD, 1992) costs were increased to reflect the measures undertaken to assure continuing good performance of control techniques. Some of the abatement techniques are not effective during some periods of operation, e.g., start-up or shut-down of facilities, short vehicle trips. This results in decreasing overall emission reduction efficiency of control technique and is reflected in some studies in terms of lower efficiencies assumed for specific techniques.

Different materials change costs. In combustion engines, catalysts for reducing VOCs use different metals, such as platinum-rhodium, which increase the cost of the pollution control technology. As technologies develop, substitutes for expensive components will be replaced with less expensive alternatives. Examples of this include the decreasing costs of electronic sensors used to monitor temperature and emissions, and ceramic components, as used in engine blocks to allow higher operating temperatures.

Economies of scale. Cost-effectiveness varies depending upon the size of the facility and on

[1] Estimated costs for three-way catalyst are 2390 ECU/ton of NO_x and VOC abated (OECD, 1992) but these costs would be only 670 ECU/ton when abated CO would be added.

the expense of retrofitting existing equipment or installing new technologies. This specifically applies to solvents, chemical plants, refineries, and gasoline stations. Different studies tend to make different assumptions.

4.2 Cost-effectiveness of control options

Bearing in mind the above range in cost estimates and removal efficiencies, *Table 12* lists the control strategies from each sector with the lowest cost and removal efficiency of at least 90 percent. These control options appear to be the most cost-effective, meaning least cost for greatest removal efficiency.

Table 12: Summary of least expensive VOC control options by sector with at least 90 percent removal efficiency

Sector	**Control Option**	**Cost (1987 ECU/ton)**
Gasoline distribution	Secondary seals on tanks	0 (a)
Chemical	Flaring	123 (b)
Refineries	Floating covers on wastewater separators	165 (c)
Ind. solvents	Carbon adsorption (general use)	193 (d)
Transport	On-board emission controls (large canisters)	200 (e)
Non-industrial solvents	Powder coatings	514 (f)

(a) OECD, 1992, p. 65
(b) ECE, 1990, p. 363
(c) OECD, 1992, p. 60
(d) OECD, 1992, p. 71
(e) ECE, 1990, p. 346
(f) OECD, 1992, p. 70

Examining alternatives across all sectors, the control options that appear most cost-effective commonly require less investment and infrastructure. The ten control options with the lowest cost are illustrated below in *Table 13* [see *Appendix* for a complete list of alternatives, sorted by least cost and highest removal efficiency].

Table 13: The ten VOC control technologies with lowest cost

	Control Option/Sector	**VOC Removal Efficiency (%)**	**Avg. Cost (ECU/ton)**
1.	Secondary seals/gasoline dist.	97	-338 (a)
2.	Water base wood paint/solvent use	65	0 (b)
3.	Machine covers/ind. solvent use	60	0 (c)
4.	High solids paint/solvent use	45	0 (d)
5.	Carbon treatment/ind. solvent use	70	15 (e)
6.	Vapor balance/gasoline dist.	95	16 (e)
7.	Cetane fuel additive/transport	15	109 (f)
8.	Flaring/chemical industry	98	123 (g)
9.	Secondary seals/refineries	89	163 (h)
10.	Floating covers on wastewater sep./refineries	90	165 (i)

(a) OECD, 1992, p. 65
(b) OECD, 1992, p. 78
(c) OECD, 1992, p. 75
(d) OECD, 1992, p. 70
(e) VHB, 1989, p. 25
(f) OECD. 1992, p. 48
(g) ECE, 1990, p. 363
(h) OECD, 1992, p. 61
(i) OECD, 1992, p. 60

4.3 Recommendations for further research

Determining cost-effectiveness of various abatement techniques requires well documented information on emissions, reduction efficiency, investment and operating costs. Several available studies as well as ongoing projects provide necessary information but often are poorly documented and consequently incomparable. There is a need for further improvement in emission factor estimates (based on measurements) as well as consistent documentation of applied methodologies and assumptions in cost calculation.

Determining how the control costs for different air pollution species were allocated in existing studies is another issue for further research.

Including other pollutants in the analysis might result in decrease or increase of cost-effectiveness estimates. Further collection of costs, increasing experience and information in the field will improve the accuracy and availability of estimates. Likewise, as more countries implement pollution control policies and regulations, new estimates will be documented. It is important to recognize that analyses limited to only specific pollutants might produce different recommendations as compared to those studies where other (all) pollutants are considered.

As the examples of control options illustrate, the range in some estimates makes it difficult to prioritize different control alternatives. For example, vapor balancing at service stations is reported to cost between 16 to 5820 ECUs per ton VOC (see *Table 11*). More precise information for these estimates will be required in order to evaluate control options and make policy recommendations in the future.

Uncertainty of cost-effectiveness estimates depends on quality of data on emissions, abatement efficiency and costs (including credits from solvent recovery) and has not been assessed in this report. In the reviewed studies the accuracy of cost estimates is given very seldom. One of the examples is the OECD study (OECD, 1992) where the accuracy of cost data for lean concept engines and three-way catalytic converters was assessed at plus or minus 30 to 50 percent. This is possibly because the presented costs reflect consumer prices, not real resource costs and therefore they are most likely higher than real economic costs. The uncertainty of emission or abatement efficiency estimates is given more often and for various sectors. As long as the error is systematic across all sectors it is not critical from the cost-efficiency calculation viewpoint. However, some studies suggest that uncertainty in emission estimates differs substantially for various sectors[2] (Winiwarter, 1993). There are several studies where uncertainty of traffic emissions has been assessed (Eggleston, 1993; Croes and Fujita, 1993; Vlieger, 1993) and the results are similar giving values around 30%. This might suggest that uncertainty of cost estimates of abatement techniques in various sectors is most likely different. More research is required to estimate the uncertainties of both emission and cost estimates especially on an international basis as the figures might vary considerably among different countries. The country-specific information is very important for development of cost-efficient emission reduction scenarios.

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[2] For example: domestic combustion - 66%, industry - 11%, transport - 30%.

Further research in this area is critical in the effort to reach the goal of gathering the necessary inputs for a RAINS ozone model. The following steps are recommended:

- Reduce the number of control options, based upon objective criteria;
- Collect necessary statistics or other relevant information in order to perform aggregation of detailed information for sub-sectors into categories distinguished in the RAINS ozone model;
- Develop a national cost curve for at least one country as an example of ranking emission control options;
- Focus on greatest potential reductions from control options. Apply emission factors to each sector and evaluate where the greatest emission reductions can be achieved;
- Collect appropriate information to develop emission projections;
- Perform sensitivity analyses to other parameters in order to assess the ranges of uncertainty.

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Appendix

Appendix

VOC Control Technology and Costs

	Sector	Control Option	VOC Removal Efficiency (%)	Avg. Cost ECU / Ton (1987)
1	Gasoline distr: Transfer & depot	rim-mounted sec. seals on tanks	97	-338
2	Non- Ind. Solvent - Architectural	water base paint for wood	65	0
3	Solvent Use - Metal Degreasing	machine covers, chilled frbd & c ads.	60	0
4	Non- Ind. Solvent - Architectural	high solids paint	45	0
5	Solvent Use - Metal Degreasing	ind. metal cleaning, carbon treat	70	15
6	Gasoline distr: Service stations	vapor balance	95	16
7	Transport - Heavy Duty Trucks	cetane improvement by additive	15	109
8	Chemical Industry	flaring	98	123
9	Refineries: Stor. & Handling	storage, secondary seals (gas prod)	89	163
10	Refineries: Stor. & Handling	floating covers on wastewater sep.	90	165
11	Gasoline distr: Service stations	vapor recovery (fuel markt)	98	172
12	Solvent Use - painting	low solvent coatings for vehicle repair	70	189
13	Solvent Use - industrial	carbon adsorption	90	193
14	Refineries: Stor. & Handling	fugitive emission - quarterly	80	193
15	On board emission control	lg canisters (all evap. emiss)	90	200
16	Chemical Industry	ink and paint manufacturing	40	218
17	Chemical Industry	catalytic incineration	98	229
18	Gasoline distr: Transfer & depot	Transfer /vapor balancing	98	286
19	Gasoline distr: Service stations	vapor balance (med)	98	286
20	Transport - On board emis. control	evaporative losses	90	291
21	Transport - Diesel vehicles & LDV	Autos -Improved diesel fuel quality	15	300
22	Solvent Use - painting	carbon adsorption on auto. paint	99	310
23	Transport - Diesel vehicles & LDV	LDV - improved diesel fuel quality	20	324
24	Solvent Use - printing	Roto - & flexography water base ink	70	419
25	Solvent Use - industrial	catalytic incineration	90	502
26	Non- Ind. Solvent - Architectural	powder coatings	100	514
27	Non- Ind. Solvent - Architectural	water based paints	82	514
28	Non - Ind. Solvent - Domestic	low solvent coatings (dom & ind)	73	514
29	Solvent Use - printing	industry, carbon treatment	85	713
30	Solvent Use - industrial	thermal incineration	90	768
31	On board emission control	vapor recovery	95	780
32	Non - Ind. Solvent - Dry cleaning	dry cleaning, closed system	99	789
33	Solvent Use - painting	auto - surface coating, process chang	70	797

Appendix

VOC Control Technology and Costs

Sector	Control Option	VOC Removal Efficiency (%)	Avg. Cost ECU / Ton (1987)
34 Solvent Use - printing	printing, process change	70	797
35 Non- Ind. Solvent - Architectural	comm. - to water based coat	25	896
36 Transport - gas auto & LDV	3-way catalytic converter	80	920
37 Gasoline distr: Service stations	vapor balance	78	968
38 Transport - gas auto & LDV	U.S. 1985 standards(3-way cat.)	90	1018
39 Chemical Industry	formaldehyde incineration	98	1133
40 Transport - On board emission con	refuelling losses	90	1165
41 Transport - Heavy Duty Trucks	cetane density improv. by process	15	1269
42 Transport - Diesel vehicles & LDV	US 1991 stds.(engine redesign)	50	1387
43 Non - Ind. Solvent - Dry cleaning	dry cleaning	50	1491
44 Transport - other	rail	89	1529
45 Gasoline dist: refinery dispatch	Loading at ref / vapor recovery	89	1580
46 Transport - gas auto & LDV	engine modifications	35	1582
47 Transport - gas auto & LDV	EEC Luxembourg (EGR & lean burn)	50	1595
48 Transport - gas auto & LDV	engine modification & EGR	35	1687
49 Gasoline distr: Service stations	gas refueling vapor bal (med size)	69	1704
50 Non - Ind. Solvent - Domestic	process change (solvent use)	90	1791
51 Transport - gas auto & LDV	oxidation catalyst - LDV	55	1896
52 Transport - gas auto & LDV	oxidation catalyst	90	1958
53 Refineries: Process	gas volatility reduction	13	2006
54 Refineries: Stor. & Handling	internal floating deck	54	2088
55 Transport - gas auto & LDV	3-way catalyst and elec. controls	80	2265
56 Solvent Use - painting	beverage cans, incineration	57	2319
57 Transport - gas auto & LDV	3-way catalyst w/I&M	75	2433
58 Solvent Use - painting	auto - surface coating, cat incin.	80	2817
59 Chemical Industry	thermal incin. of paint manuf.	91	2823
60 Transport - gas auto & LDV	oxidation catalyst - auto	55	2990
61 Solvent Use - industrial	industry - misc.	90	3506
62 Transport - other	barge	89	3860
63 Transport - gas auto & LDV	oxidation catalyst w/I&M - auto	55	4032
64 Solvent Use - printing	printing, incineration	90	4225
65 Transport - Motorcycles	engine modifications & EGR	35	4297
66 Non - Ind. Solvent - Dry cleaning	dry cleaning, carbon treatment	95	4390
67 Transport - Motorcycles	oxidation catalyst	55	4731
68 Solvent Use - printing	lithography; catalytic incin/ heat rec.	69	5389
69 Gasoline distr: Service stations	vapor balance	56	5820
70 Transport - gas auto & LDV	oxidation catalyst - auto	55	6177
71 Transport - Motorcycles	oxidation catalyst w/ I&M	75	7562
72 Solvent Use - printing	lithography: thermal incin/heat rec.	69	7881
73 Transport - gas auto & LDV	oxidation catalyst w/ I&M - auto	75	8789
74 Solvent Use - painting	auto - surface coating, higher solids cc	88	8958
75 Refineries: Stor. & Handling	retrofitting fixed roof tanks w/int covers	89	10435